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**ABSTRACT:** Recent animal experiments have shown that up to 37% of muscle force may be transmitted to adjacent structures rather than reach the insertion of the muscle's tendon, and that the extent of such force transmission depends on the length and relative position of these structures. We tested whether the force-length characteristics of the distally tenotomized human flexor carpi ulnaris muscle (FCU) of nine patients with cerebral palsy varied with the change of relative length of adjacent structures induced by a change of wrist position. In four patients, the FCU exerted up to 40% more active force in a flexed wrist position at short FCU length, whereas the active force was not significantly higher in the other five. In the same manner, passive force-length characteristics of the spastic FCU changed upon changes in wrist position. Variability in myofascial force transmission may partly explain the variability in success of the FCU-transfer.

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## SPASTIC MUSCLE PROPERTIES ARE AFFECTED BY LENGTH CHANGES OF ADJACENT STRUCTURES

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In most drawings and descriptions, muscles are distinguished as anatomically separate structures. Likewise, mechanical studies of muscles have focused on the behavior of muscles, or even muscle fibers, that were separated from their surroundings. From these types of studies, much has been learned on the intrinsic properties of muscle. However, such studies reflect the common understanding that the force transmission of a muscle is independent of adjacent muscles and structures. The anatomical truth, however, is that most muscles are connected to adjacent muscles by intermuscular connective tissue, and to bones, fascial planes, vessels, and nerves by extramuscular connective tissue. These inter- and extramuscular connections have been ignored in muscle research and surgery and, hence, are usually dissected without much concern.

Recently, however, the interaction of muscles through these connections has been shown to affect muscle properties significantly.<sup>4,7,10,11,17,19</sup> This has led to the idea that forces are transmitted not only to the tendon by sarcomeres lined up in-series within a muscle fiber but, also, to sarcomeres that are parallel to each other.<sup>5,7</sup> Moreover, up to 37% of maximal muscle force may be transmitted to adjacent structures through inter- and extramuscular connective tissues,<sup>5,7</sup> rather than exerted at the insertion of the muscle's tendon.<sup>13</sup> This transmission of force outside the myotendinous junction is termed myofascial force transmission.<sup>5</sup> In experimental conditions, the extent of such inter- and extramuscular force transmission has depended on the length and relative position of the involved structures.<sup>8,14</sup> As this may also be true in human muscle, the purpose of this study was to test the hypothesis that the force-length characteristics of the human flexor carpi ulnaris muscle (FCU) measured at its tendon vary with the relative length of its adjacent structures.

Force-length curves of the distally tenotomized FCU were constructed at a series of FCU lengths from intraoperative force measurements during tendon transfer surgery in patients with cerebral palsy, while the wrist was held in extension and in flexion. With the wrist in extension, the flexor digitorum

**Abbreviations:** FCU, flexor carpi ulnaris muscle; FDP, flexor digitorum profundus muscle; FDS, flexor digitorum sublimis muscle;  $L_{\max}$ , muscle length at maximum force

**Key words:** force-length curve; muscle; myofascial force transmission; spasticity; tendon transfer

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profundus (FDP) and flexor digitorum sublimis (FDS), as well as extramuscular structures adjacent to the cut FCU, are at long length relative to the FCU. In contrast, the FDP and FDS and the extramuscular structures are at a short length relative to the FCU when the wrist is flexed. Varying the wrist position thus allowed the position of the involved structures to change relative to each other. Additionally, when length and position changes of adjacent tissues affected FCU length–force characteristics, it was questioned whether such effects related to clinical measures such as the existence of a hypoextensibility of the finger flexors and the severity of wrist flexion deformity.

## MATERIALS AND METHODS

**Patients.** The study protocol was approved by our local ethical committee and adhered to the guidelines of the 1975 Declaration of Helsinki. After informed consent was obtained, six female and three male patients (mean age, 16 years; range 9–23 years) with hemiplegic cerebral palsy underwent surgery for correction of a flexion deformity at the wrist. Patients were under general anesthesia without the use of muscle relaxants or a tourniquet. Although several additional surgical procedures were performed for clinical purposes in every patient, the experiments were performed first in all.

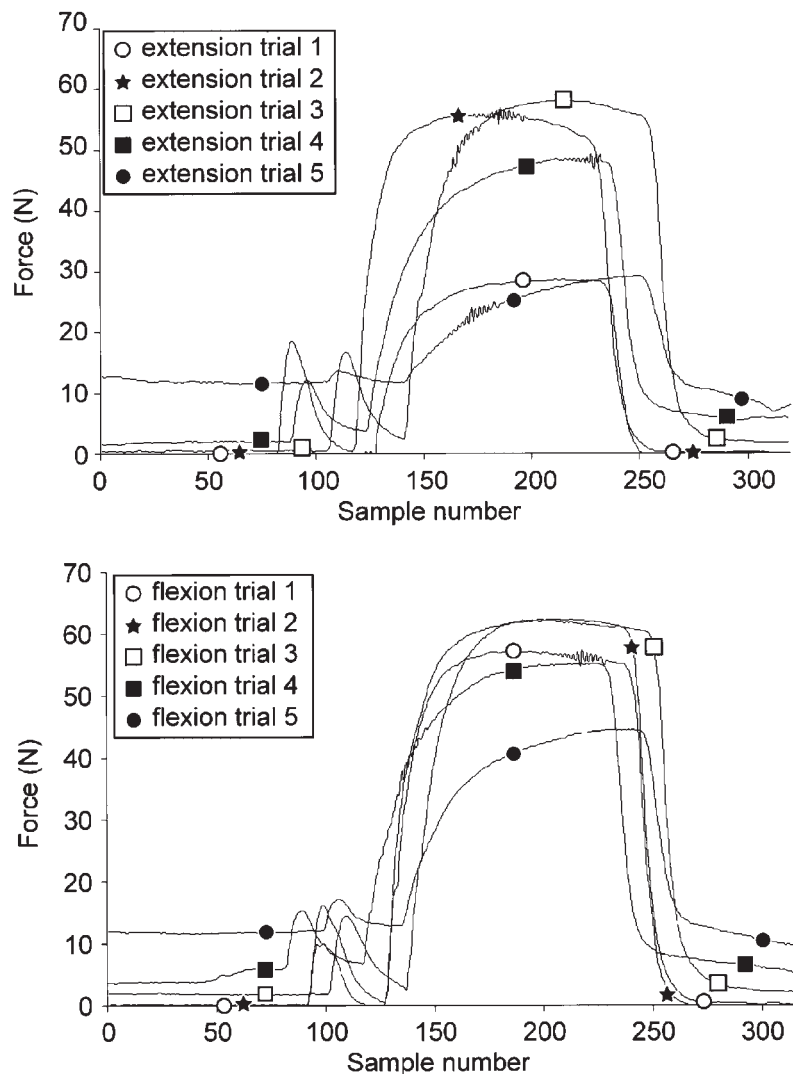
**Preoperative Clinical Measurements.** Maximal passive extension of the wrist was measured prior to surgery while patients were under anesthesia to quantify the severity of wrist deformity. Subsequently, the wrist was held in a neutral position and the fingers were extended. The surgeon (M. K.) decided clinically whether the finger flexor muscles were considered severely hypoextensible (the fingers could not be stretched at all), moderately hypoextensible (the fingers could only be stretched when the wrist was flexed), or not hypoextensible (the fingers could be fully stretched).

**Surgical Technique and Intraoperative Measurements.** The conditions and validation of the experimental method were previously described in detail.<sup>18</sup> An incision from the pisiform bone along the ulnar border of the FCU was made over the distal third of the forearm. Subsequently, the FCU tendon was cut just proximal to its insertion on the pisiform bone to be dissected up to the insertion of the most distal muscle fiber in the FCU tendon. This distal muscle fiber was marked with a thin suture. Care was taken that the muscle belly remained optimally unharmed

in its in vivo environment in all patients. A Kirschner wire was drilled in the center of the medial epicondyle. FCU muscle length was defined as the distance between this wire and the suture marking. A metal ring was sutured onto the distal tendon. A strain gauge was attached to the metal ring on the distal tendon of the FCU and to a metal bar that was attached to the Kirschner wire in the medial epicondyle. The strain gauge was kept aligned with the FCU. During measurement, the elbow was held at a constant angle of 30 degrees of flexion in all patients. A pilot study had shown that some initial contractions had to be induced to increase the reproducibility of the measurements as previous activity at a long length initially affects the measured force at short lengths (Smeulders et al., unpublished data). Therefore, initial isometric contractions were induced by transcutaneous electrical stimulation of the ulnar nerve at long and short FCU lengths until the effects of previous activity at the long length were eliminated.<sup>6</sup> A single maximal contraction reliably reflects the force–length relationship at a given muscle length,<sup>18</sup> and a series of measurements was obtained in two conditions: when the wrist was held (1) in 90 degrees of flexion, and (2) in maximal extension. The order in which each experimental condition was first performed alternated in consecutive patients to exclude structural bias.

At consecutive muscle lengths (0.5-cm increments), a series of maximal tetanic contractions of the FCU (Fig. 1) were induced by supramaximal transcutaneous electrical stimulation of the ulnar nerve (140 mA, 50 Hz, 0.1-ms pulse duration, 1,400-ms stimulus duration<sup>18</sup>), using two gel-filled skin electrodes (Red Dot 2560, 3Com Inc., Minneapolis, Minnesota) that were pasted on the skin directly overlying the cubital tunnel at the elbow. For each patient, each series of active and passive force–length measurements included a minimum of five, and a maximum of seven FCU lengths. A 2-min rest period between each measurement allowed the FCU to recover.<sup>18</sup> Just before and during stimulation, the strain gauge signal was analog-to-digital converted and stored in a computer. The experimental preparations and collection of data took approximately 30 min.

**Data Analysis.** Two representative data points from each tetanic contractions were identified for use in the construction of active and passive force–length curves: one just prior to stimulation, representing the passive muscle force, and one at the tetanic plateau, representing the total of active and passive muscle forces. Active force was defined as this total



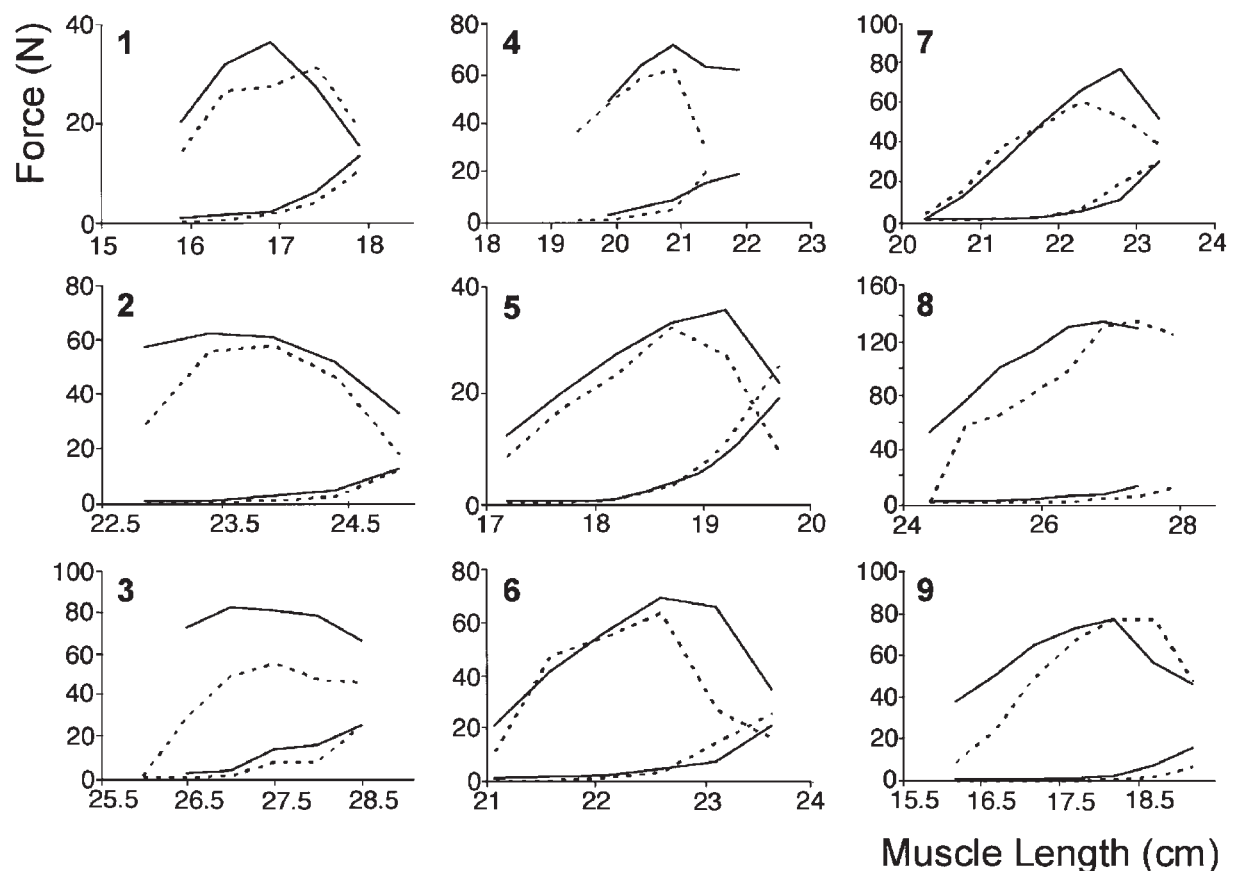
**FIGURE 1.** Raw data of two representative sets of five maximal tetanic contractions of the FCU of one patient at five consecutive FCU lengths. Measurements were done in two conditions: with the wrist held in extension (upper graph) and with the wrist held in flexion (lower graph). The range of consecutive FCU lengths was the same in the two conditions.

minus the passive force. Maximal FCU force was defined as the force corresponding with the top of the curve of active force, and the corresponding FCU length as the length of maximum force ( $L_{\max F}$ ). All force values were normalized for maximal FCU force in the extended wrist position. Because the absolute length at which the measurements had started and the absolute measured range of lengths differed in every patient, the length relative to  $L_{\max F}$  was calculated to allow for comparison between patients. Five data points within the part of the force-length profile for which data of all patients was available at length intervals of 5 mm were used for averaging and statistical analysis. Averages and standard errors of the force-length data of each patient were calculated.

Two-way ANOVA for repeated measurements was performed to test for differences in force-length curves between the two experimental conditions. Pearson chi-square statistic was used to check whether the order of measurements influenced the results. Somer's D statistic was used to verify whether relations between conditions and clinical measures were present. An SPSS 11.5.1 package (SPSS Inc., Chicago, Illinois) was used for all statistical calculations.

## RESULTS

Although considerable difference existed in FCU force-length curves among the patients (Fig. 2), the maximum active force that the FCU exerted on the



**FIGURE 2.** Individual active and passive FCU force-length curves of nine patients with cerebral palsy with the wrist held in two positions: in flexion (solid line), and extension (dashed line). The X-axes show FCU lengths (cm), the Y-axes show the FCU forces (N). Note the large individual differences in active and passive force and in muscle length.

force transducer was highest when the wrist was held in flexion in all but two patients (Table 1). In three patients (Nos. 3, 8, and 9), little or no active force

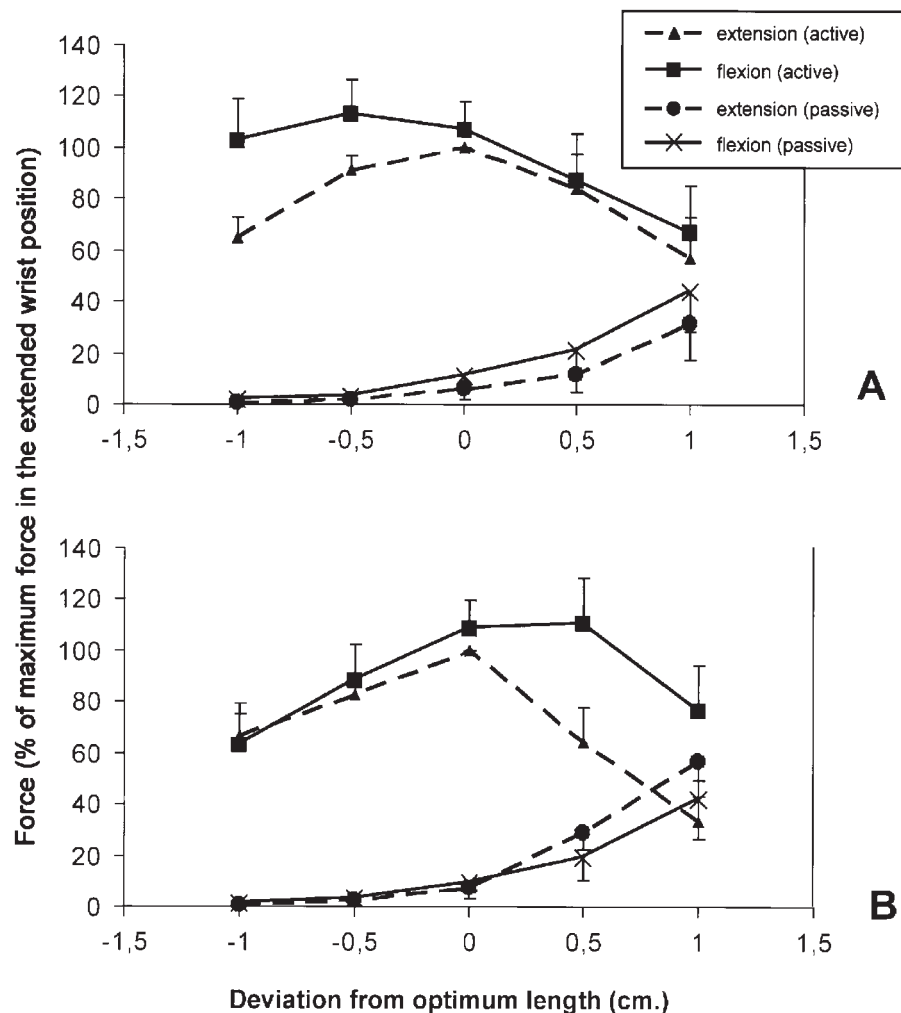
was exerted at the tendon at short FCU length when the wrist was held in extension, whereas this force was high at the identical FCU length with the wrist in

**Table 1.** Individual force-length characteristics of the FCU of nine patients.\*

Patient	Maximum extension (degrees)	Fingers extensible	Fmax <sub>act</sub> ext (N)	Fmax <sub>act</sub> flex (N)	L <sub>maxF</sub> ext (cm)	L <sub>maxF</sub> flex (cm)	Group <sup>†</sup>
1	-55	0	31	36	16.8	16.3	1
2	75	0	58	62	23.9	23.4	1
3	0	2	55	82	27.5	27.0	1
4	20	1	62	72	21.4	20.9	2
5	90	0	33	36	18.7	19.2	2
6	30	1	64	69	21.6	21.6	2
7	10	1	60	77	22.3	22.8	2
8	60	1	135	134	27.4	26.9	1
9	75	0	78	76	18.7	18.2	1

\*Maximum extension, maximum passive extension angle during anesthesia; Fingers extensible, presence of hypoextensibility of fingers (0 = not hypoextensible; 1 = moderately hypoextensible; 2 = severely hypoextensible); Fmax<sub>act</sub> ext, FCU maximum active force in extended wrist position; Fmax<sub>act</sub> flex, FCU maximum active force in flexed wrist position; L<sub>maxF</sub> ext, FCU length corresponding with maximum active force in extended wrist position; L<sub>maxF</sub> flex, FCU length corresponding with maximum active force in flexed wrist position.

<sup>†</sup>Patients were divided into two groups based on the maximum passive force and the shape of the active length-force curve.



**FIGURE 3.** Mean active and passive force–length curve of the spastic FCU patients with cerebral palsy with the wrist held in two positions: in flexion (solid line), and in extension (dashed line). Two groups were distinguished based on the shape of the curves of the individual patients (**A**, **B**). Force data are normalized for maximum active force in extension.

a flexed position (Fig. 2). Average maximum active force of all patients was 64.0 N (SD, 27.2 N) when the wrist was held extended, and 71.6 N (SD, 25.1 N) when it was held in flexion.

The effect of wrist position on passive FCU force was less uniform. In a first group of five patients (Table 1), the mean peak passive force was 5.6 N (SD, 2.7 N) higher when the wrist was held in flexion. In contrast, in the other four patients (Table 1), the mean peak passive force was on average 6.3 N (SD, 1.5 N) higher when the wrist was in extension. Still, the greatest difference between the force with the wrist in extension and in flexion was found at greater FCU lengths in both groups (Fig. 2).

The effect of wrist position on the active FCU force, likewise, varied at different FCU lengths. In the first group of five patients (Fig. 3A), the muscle

exerted 40% more active force in a flexed-wrist position at short FCU (i.e.,  $-1.0$  cm below  $L_{\max F}$  of the curve with the wrist in extension), whereas the active force in a flexed-wrist position was 0%–15% higher at greater FCU length (i.e., 0, 0.5, and 1 cm from  $L_{\max F}$  of the curve with the wrist in extension). In the second group of four patients, the FCU exerted 0%–10% more active force at the distal tendon in a flexed than extended wrist position at short FCU length up to FCU  $L_{\max F}$  of the curve with the wrist in extension, and up to approximately 40% more active force at higher FCU length (Fig. 3B).

Analysis of variance indicated that active force–length curves of the FCU were not significantly affected by changing wrist position in the first group ( $P = 0.204$ ), although a clear trend was present towards a higher active force in a flexed-wrist posi-



tion. Passive force–length curves, however, were significantly different for the two wrist positions in this group ( $P = 0.022$ ). Moreover, the maximum active force in this group was attained at 0.5 cm shorter FCU length in the flexed-wrist than the extended-wrist position. In the second group, active force–length curves and passive force–length curves of the FCU were affected significantly by changing wrist position ( $P = 0.019$  and  $0.002$ , respectively). In this group, the maximum active force was reached at an approximately 0.5 cm greater FCU length when the wrist was held in a flexed rather than extended wrist position.

There was no relation between the type of effects (i.e., group 1 or group 2) and the order at which the measurements were performed (chi-square = 9.0,  $P = 0.253$ ). Likewise, the maximal wrist extension angle and the presence of contracture of finger muscles in spastic patients did not significantly correlate with the type of effects (Somer's  $D = -0.057$ ,  $P = 0.811$ ; and Somer's  $D = -0.162$ ,  $P = 0.582$ ).

## DISCUSSION

The present study shows that the force–length characteristics of spastic muscles change as a result of relative length differences with their surroundings. These length differences may result in a changed contribution of myofascial force transmission. With a change in wrist position, the length of the FDS and FDP and the extramuscular tissues adjacent to the FCU varies relatively to that of the distally cut FCU, thereby straining or relaxing the inter- and extramuscular connections between the FCU and its adjacent tissues.<sup>8</sup> Such straining of connections may alter their compliance and make them stiffer.<sup>2</sup> Because the structure that is stiffest transmits the highest force, the fraction of force that may be transmitted through the inter- and extramuscular connective tissues depends on the relative length and positions of the muscles and adjacent structures involved. Depending on the relative compliance and direction of pull of these connections, force generated by the FCU may either dissipate through the myofascial pathway, or force exerted by structures other than the FCU may be added to FCU force. This, in turn, results in different forces being exerted at the FCU tendon for different wrist positions.

We found that the active force exerted at the FCU tendon at a particular FCU length may vary by up to 40% with varying lengths of its adjacent structures. The actual effect of wrist position on the FCU force–length characteristics was not the same in every patient. In some, the force–length curves were

affected most for short FCU, whereas in others the effects were most significant at long FCU lengths. This corresponded to an opposing effect of wrist position on passive force–length curves. That the passive force in wrist flexion was sometimes higher than in wrist extension at longer FCU length, whereas it was lower in other patients, may be explained by the individual differences among patients of relative length and direction of pull of the inter- and extramuscular tissues. As such, they may add to the passive FCU force pulling on its tendon in some patients, whereas in others they may diminish the passive FCU force resulting in a lower force measured at the tendon. Initial length differences between the FCU and its surroundings due to differences in clinical measures of the severity of the wrist deformity such as the maximal wrist extension angle and the presence of contracture of finger muscles in spastic patients may explain these differences. However, we were unable to substantiate this possibility as the relations between the effect of wrist position and clinical measures were not significant.

The distinction between the two groups of patients was based on the specific effects of wrist position on the active and passive length–force curves. Ideally, this distinction would have been based on a hypothesis, rather than based on study observations. We distinguished the patients based on an arbitrary criterion. Nonetheless, it is possible that the distinction of two groups is an underestimation of the real variability in patient population, and subdivision into more groups based on specific characteristics of the myofascial pathways may be necessary in the future. To develop an accurate theory to explain such variability requires more knowledge of the length, position, and stiffness of the involved tissues relative to each other in different conditions. Still, the absence of any relation between the clinically manifest shortness of FDS and FDP, the severity in the limitation of wrist extension, and the specific effects of wrist position on the length–force curves indicate that the cause of the variability among patients may be rather complex.

**Implications for Muscle Models.** Direct measurement of active muscle forces in humans have rarely been performed<sup>3,12,15,16,18</sup> because direct access to muscle is limited exclusively to the operating theater. Performing tendon transposition of the FCU in patients with cerebral palsy yields a unique opportunity to directly measure active and passive muscle forces because the FCU is relatively easy to stimulate electrically, and the muscle's distal tendon is cut, allowing for a force transducer to be positioned

in-series with it.<sup>18</sup> Muscles of patients with cerebral palsy may not be similar to healthy muscle and the results of the present study should not be extrapolated to healthy muscles without due consideration. Still, inter- and extramuscular connections exist in healthy rat muscle<sup>9</sup> and can be expected in healthy human limbs. Moreover, differences in length and position of the FCU to the FDS and FDP commonly occur in vivo as a result of the differences in muscle excursion during flexion and extension of the fingers, and of the differences in moment arms at the wrist.<sup>1</sup>

The effects described may impede efforts to quantify individual muscle forces with indirect, in vivo measurements. For example, the minimum length at which the FCU is able to exert any active force (its slack length) seemed to be shorter when the wrist is in flexion than in extension in some of the studied patients. Observation of such a shift of the slack length would not be possible in muscles studied in isolation from their surroundings. The relative position to its surroundings may, thus, be an additional parameter to be considered when predicting in vivo muscle function on the basis of conventional muscle models.

**Implications for Clinical Practice.** Our observations show that muscle function is even more complex than assumed and, so far, no answers have been provided for clinical questions such as how surgery should be adapted for an optimal result, at what tension a donor muscle should be positioned, and to what degree a spastic muscle differs from a healthy one. Still, we provide a possible explanation for part of the unpredictability of the results of muscle transpositions in patients with spasticity. The results from such surgical interventions have always been unpredictable, and sometimes do not meet the expectations of patients (and their doctors). Our observations indicate co-determinants of muscle function that previously were not considered seriously. The significant effects of myofascial force transmission on muscle length–force characteristics suggest that, in addition to absolute muscle length, the length and position of a muscle relative to its adjacent tissues also determine the active and passive force that it exerts at a particular tendon.

We still lack information on the absolute stiffness of the inter- and extramuscular connections in spastic limbs, on the relative length of the FCU to the FDS and FDP, and on the direction of pull of the connections between them. It is clear, however, that the effect on net FCU force exertion at its transposed tendon may vary by up to 40%. This suggests

that the inter- and extramuscular connective tissues have different properties in different patients, and this difference may be related to the variability of clinical results occurring after tendon transfer surgery among patients. But how important is myofascial force transmission for in vivo muscle function? The effects of relative length and positional differences were studied in a rather artificial condition with the FCU dissected partially and attached to a force-transducer. Obviously, the intact FCU would have been lengthened and shortened along with the surrounding tissues during unhampered in vivo flexion and extension of the wrist and, as a result, relative length and position differences would have been smaller. Still, the experiments were a priori performed to show the effect in principle of a change in relative position and length of adjacent structures. Moreover, unlike FCU, the FDS also crosses the metacarpal and proximal interphalangeal joints, and the FDP even the distal interphalangeal joint. Maximal flexion and extension of these joints have been estimated to result in an excursion of approximately 3.25 cm of the FDS and FDP when the wrist is held in a neutral position.<sup>2</sup> The relative length differences observed between the FCU and the FDS and FDP during our experiments were comparable to those occurring during tasks of daily living such as grasping a glass, as they approximated 3 cm.

After transposition of the FCU to the extensor carpi radialis brevis muscle in patients with cerebral palsy, the FCU is expected to become an antagonist to the FDS and FDP. This implies that whenever the FCU shortens, the FDS and FDP are being stretched, and vice versa, thus increasing their difference in relative length and position. As a result, significant inter- and extramuscular force transmission may affect the force exerted at the transposed tendon. Although the distal part of the transferred FCU has a new route and thus new structures adjacent to it, almost half the muscle is still situated at its original location with all the intermuscular connections to the FDS and FDP intact. It may therefore be assumed that at least part of the inter- and extramuscular force transmission remains intact. Through this part, the FCU force that is transmitted from the muscle through the inter- and extramuscular pathways remains to exert a flexion moment over the wrist joint, rather than the intended extension moment.<sup>17</sup> Individual variation in differences in active and passive force–length characteristics during wrist flexion and extension may explain part of the variability of the success of the FCU-transfer that is often observed among patients with cerebral palsy. Obviously, any prediction of FCU muscle function after transfer is



further hindered by fibrosis and newly formed connections during rehabilitation. To what extent these remaining and newly formed connections influence the function of the re-routed FCU also remains subject to further study.

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